

Cold Nuclear Matter Effects on J/ψ Production with Extrinsic P_T at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC

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Abstract

We evaluate the Cold Nuclear Matter effects on J/ψ production in p Pb and PbPb collisions at the current LHC energy, taking into account the gluon shadowing and the nuclear absorption. We use the complete kinematics in the underlying $2 \rightarrow 2$ partonic process, namely $g + g \rightarrow J/\psi + g$ as expected from LO pQCD. The resulting shadowing is responsible for a large J/ψ suppression in p Pb and PbPb, and shows a strong rapidity dependence.

Keywords: J/ψ production, heavy-ion collisions, cold nuclear matter effects

1. Introduction

Relativistic nucleus-nucleus (AB) collisions are expected to produce a deconfined state of QCD matter – the Quark Gluon Plasma (QGP) – at high enough densities or temperatures. The J/ψ meson should be [1] sensitive to Hot and Dense Matter (HDM) effects, through processes like the colour Debye screening of the $c\bar{c}$ pair. A significant suppression of the J/ψ yield was observed at SPS energy by the NA50 experiment [2], and at RHIC by the PHENIX experiment in CuCu [3] and AuAu [4] collisions at $\sqrt{s_{NN}} = 200$ GeV. The data recently taken at LHC in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV will provide results at a new energy scale, providing means to further test the available models. However, concurrent mechanisms – the Cold Nuclear Matter (CNM) effects – are known to already impact the J/ψ production in proton (deuteron)-nucleus (pA or dA) collisions, where the deconfinement can not be reached. Hence, the interpretation of the results obtained in AB collisions relies on a good understanding and a proper subtraction of the CNM effects. Two CNM effects are of particular importance [5]: (i) the shadowing of the initial parton distributions (PDFs) due to the nuclear environment, and (ii) the breakup of $c\bar{c}$ pairs after multiple scatterings with the remnants of the incident nuclei, referred to as the nuclear absorption. In our previous works [6–9], we developed an exhaustive study of these effects. We confronted our results to the measurements from PHENIX [10] in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV, before giving our CNM effects estimates in CuCu and AuAu collisions. It is our purpose here to extend our results to p Pb and PbPb collisions at the current LHC energy $\sqrt{s_{NN}} = 2.76$ TeV.

As we have shown in earlier studies [6–9], considering the adequate J/ψ partonic production mechanism – either via a $2 \rightarrow 1$ or a $2 \rightarrow 2$ process – affects both the way to compute the nuclear shadowing and its expected impact on the J/ψ production. From now on, we will refer to the former scenario as the *intrinsic* scheme, and to the latter as the *extrinsic* scheme. Most studies on the J/ψ production in hadronic collisions are carried out in the intrinsic scheme. They rely on the assumption that the $c\bar{c}$ pair is produced by the fusion of two gluons carrying some intrinsic transverse momentum k_T . The partonic process being a $2 \rightarrow 1$ scattering, the sum of the gluon intrinsic k_T is transferred to

the $c\bar{c}$ pair, thus to the J/ψ since the soft hadronisation process does not alter significantly the kinematics. This is supported by the picture of the Colour Evaporation Model (CEM) at LO (see [11] and references therein) or of the Colour-Octet (CO) mechanism at α_s^2 [12]. Thus, in such approaches, the transverse momentum P_T of the J/ψ *entirely* comes from the intrinsic k_T of the initial gluons. However, the average value of k_T is not expected to go much beyond ~ 1 GeV. So this process is not sufficient to describe the P_T spectrum of quarkonia in hadron collisions [11].

In addition, recent theoretical works incorporating QCD corrections or s -channel cut contributions have emphasized [13–15] that the Colour-Singlet (CS) mediated contributions are sufficient to describe the experimental data for hadroproduction of both charmonium and bottomonium systems without the need of CO contributions. Furthermore, recent works [16] focusing on production at e^+e^- colliders have posed stringent constraints on the size of CO contributions, which are the precise ones supporting a $2 \rightarrow 1$ hadroproduction mechanism [11]. As a consequence, J/ψ production at low and mid P_T likely proceeds via a $2 \rightarrow 2$ process, such as $g + g \rightarrow J/\psi + g$, instead of a $2 \rightarrow 1$ process¹. This amounts to the bulk of the J/ψ production cross section. Consequently, one is entitled to consider that the former $2 \rightarrow 2$ kinematics i.e. the extrinsic scheme is the most appropriate to derive CNM effects at RHIC, and to provide predictions at LHC energy. In this work, we shall focus on the CNM effects expected at the current LHC energy $\sqrt{s_{NN}} = 2.76$ TeV in the extrinsic scheme. The article is organized as follows: in section 2, we will describe our model and in section 3, we will present and discuss our results.

2. Our approach

To describe the J/ψ production in nuclear collisions, our Monte Carlo framework [6, 18] is based on the probabilistic Glauber model. The nucleon-nucleon inelastic cross section at $\sqrt{s_{NN}} = 2.76$ TeV is taken to be $\sigma_{NN} = 64$ mb [19] and the maximum nucleon density to be $\rho_0 = 0.17$ nucleons/fm³. We also need to implement the partonic process for the $c\bar{c}$ production model that allows to describe the pp data, and the CNM effects.

2.1. Partonic process for the $c\bar{c}$ production

For $P_T \gtrsim 2 - 3$ GeV, most of the transverse momentum of the quarkonia should have an extrinsic origin, i.e. the J/ψ 's P_T would be balanced by the emission of a recoiling particle – a hard gluon – in the final state. The J/ψ would then be produced by gluon fusion in a $2 \rightarrow 2$ process. This emission, which is anyhow mandatory to conserve C -parity, has a definite influence on the kinematics of the J/ψ production. Indeed, for a given J/ψ momentum (thus for fixed rapidity y and P_T), the processes discussed above, i.e. the intrinsic $g + g \rightarrow c\bar{c} \rightarrow J/\psi (+X)$ and the extrinsic $g + g \rightarrow J/\psi + g$, will proceed on the average from initial gluons with different Bjorken- x . Therefore, they will be affected by different shadowing corrections.

In the intrinsic scheme, the measurement of the J/ψ momentum in pp collisions completely fixes the longitudinal momentum fraction of the initial partons: $x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(\pm y) \equiv x_{1,2}^0(y, P_T)$ with $m_T = \sqrt{M^2 + P_T^2}$, M being the J/ψ mass. On the contrary, in the extrinsic scheme, the knowledge of the y and P_T spectra is not sufficient to determine x_1 and x_2 . Actually, the presence of a final-state gluon introduces further degrees of freedom, allowing several (x_1, x_2) for a given set (y, P_T) . The four-momentum conservation results in a complex expression of x_2 as a function of (x_1, y, P_T) :

$$x_2 = \frac{x_1 m_T \sqrt{s_{NN}} e^{-y} - M^2}{\sqrt{s_{NN}} (\sqrt{s_{NN}} x_1 - m_T e^y)}.$$

Equivalently, a similar expression can be written for x_1 as a function of (x_2, y, P_T) . Even if the kinematics determines the physical phase space, models are anyhow *mandatory* to compute the proper weighting of each kinematically allowed (x_1, x_2) . This weight is simply the differential cross section at the partonic level times the gluon PDFs, i.e. $g(x_1, \mu_F) g(x_2, \mu_F) d\sigma_{gg \rightarrow J/\psi + g} / dy dP_T dx_1 dx_2$. In the present implementation of our code, we are able to use the partonic differential cross section computed from *any* theoretical approach. In this work, we shall use the Colour-Singlet Model (CSM) at LO at LHC energy, shown to be compatible [14, 20] with the magnitude of the P_T -integrated cross-section as given by the PHENIX pp data [21], the CDF $p\bar{p}$ data [22] and the LHC pp data at $\sqrt{s_{NN}} = 7$ TeV.

¹One may also go further and consider more than two particles in the final state, as expected from the real-emission contributions at NLO and NNLO [13]. It is clear from the yield polarisation [17] that these contributions start to dominate for P_T above $1 - 2m_c$. The effect of more partons in the final state is to increase the difference between the results obtained in both schemes. However the implementation of NLO and NNLO codes in a Glauber model with an inhomogeneous shadowing is not yet available.

2.2. Shadowing and nuclear absorption

To obtain the J/ψ yield in pA and AA collisions, a shadowing-correction factor has to be applied to the J/ψ yield obtained from the simple superposition of the equivalent number of pp collisions. This shadowing factor can be expressed in terms of the ratios R_i^A of the nuclear Parton Distribution Functions (nPDF) in a nucleon belonging to a nucleus A to the PDF in the free nucleon: $R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{A f_i^{\text{nucleon}}(x, Q^2)}$, $i = q, \bar{q}, g$. The numerical parameterisation of $R_i^A(x, Q^2)$ is given for all parton flavours. Here, we restrict our study to gluons since, at high energy, the J/ψ is essentially produced through gluon fusion [11]. Several shadowing parametrisations are available [23–26]. In the following, we shall restrict ourselves to EKS98 [24], which is very close to the mean in the current evaluation of the uncertainty [26] on the gluon nPDF and exhibits a moderate antishadowing. We postpone the propagation of the uncertainty on the gluon nPDF to the CNM effects evaluated at LHC energy for future studies.

The second CNM effect that we are going to take into account concerns the nuclear absorption. In the framework of the probabilistic Glauber model, this effect is usually parametrised by introducing an effective absorption cross section σ_{abs} . It reflects the break-up of correlated $c\bar{c}$ pairs due to inelastic scattering with the remaining nucleons from the incident cold nuclei. The value of σ_{abs} is unknown at LHC. At high energy, the heavy state in the projectile should undergo a coherent scattering off the nucleons of the target nucleus [27], in contrast with the incoherent, longitudinally ordered scattering that takes place at low energies. As argued in [28, 29], this should lead to a decrease of σ_{abs} with increasing $\sqrt{s_{NN}}$. The systematic study of many experimental data indicate that σ_{abs} appears either constant [30] or decreasing [31] with energy. Hence, we can consider our estimates [8, 9] of σ_{abs} at RHIC energy as upper bounds for the value of σ_{abs} at LHC. We choose three values of σ_{abs} that should span that interval ($\sigma_{\text{abs}} = 0, 1.5, 2.8$ mb).

3. Results and discussion

In the following, we present our results for the J/ψ nuclear modification factor due to CNM effects in the extrinsic scheme in pPb and $PbPb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV: $R_{AB} = dN_{AB}^{J/\psi} / \langle N_{\text{coll}} \rangle dN_{pp}^{J/\psi}$, where $dN_{AB}^{J/\psi}$ ($dN_{pp}^{J/\psi}$) is the observed J/ψ yield in $AB = pPb, PbPb$ (pp) collisions and $\langle N_{\text{coll}} \rangle$ is the average number of nucleon-nucleon collisions occurring in one pPb or $PbPb$ collision. Without nuclear effects, R_{AB} should equal unity.

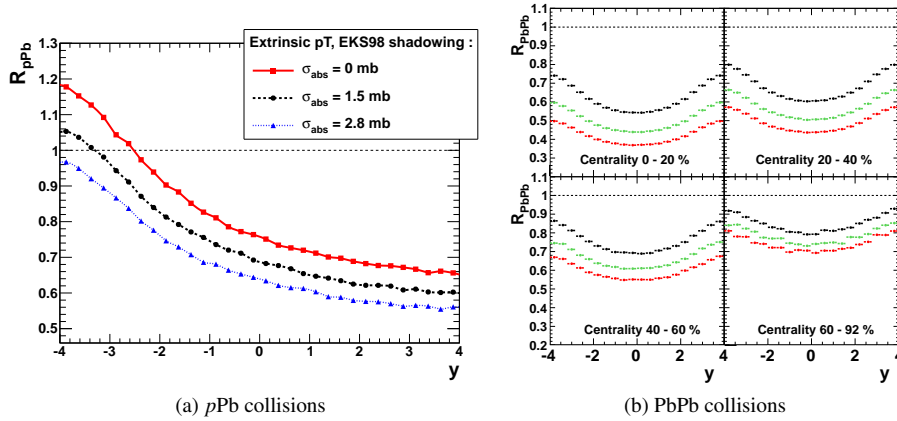


Figure 1: (Color online) J/ψ nuclear modification factor versus y in pPb and $PbPb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV, using EKS98 [24] gluon shadowing parametrisation and three values of σ_{abs} (from top to bottom: 0, 1.5, 2.8 mb) in the extrinsic scheme. For $PbPb$ collisions, the y -dependence is shown for various centrality selections.

In Fig. 1a, we show R_{pPb} versus y . The curve with no absorption allows to highlight the strong rapidity dependence of the shadowing. We can also notice that the shadowing alone should already be responsible for a quite large amount of J/ψ suppression, up to 34 % at $y = 4$. This is expected due to the very small x -region in the gluon nPDF that becomes accessible at LHC energy (down to 10^{-5}). Fig. 1b shows that the y -dependence of R_{PbPb} is similar for all the centrality bins, with a dip at mid- y . This shape is the opposite of the one obtained at RHIC energy [6, 8], with a peak at mid- y . Here, R_{PbPb} is systematically smaller at mid- y than at forward- y . This is also illustrated on Fig. 2, with the

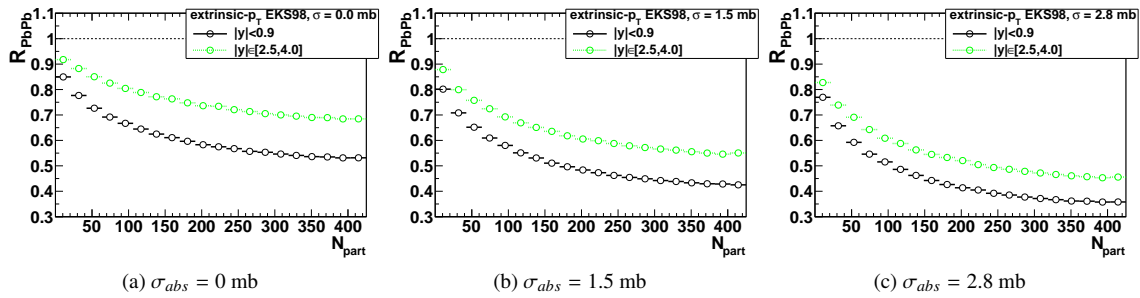


Figure 2: (Color online) J/ψ nuclear modification factor, R_{PbPb} , in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV versus N_{part} , using EKS98 [24] gluon shadowing parametrisation and three values of the nuclear absorption cross section in the extrinsic scheme. R_{PbPb} is shown for two different experimental acceptances in rapidity, $|y| < 0.9$ and $|y| \in [2.5, 4]$.

centrality dependence of R_{PbPb} for two regions in y . This behaviour of the CNM effects may partially – or completely – compensate the opposite effect expected from $c\bar{c}$ recombination, with a maximum enhancement at $y = 0$. Overall, one may observe a R_{PbPb} rather independent of y resulting of two y -dependent effects.

E.G.F. thanks Ministerios de Educacion y Ciencia of Spain (FPA2008-03961-E/IN2P3) for financial support.

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